

# Calorimeter-only analysis of the Fermi Large Area Telescope

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Above tens of GeV,  $\gamma$ -ray observations with the *Fermi* Large Area Telescope (LAT) can be dominated by statistical uncertainties due to the low flux of sources and the limited acceptance. We are developing a new event class which can improve the acceptance: the “Calorimeter-only (CalOnly)” event class. The LAT has three detectors: the tracker, the calorimeter, and the anti-coincidence detector. While the conventional event classes require information from the tracker, the CalOnly event class is meant to be used when there is no usable tracker information. Although CalOnly events have poor angular resolution and a worse signal/background separation compared to those LAT events with usable tracker information, they can increase the instrument acceptance above few tens of GeV, where the performance of Fermi-LAT is limited by low photon statistics. In these proceedings we explain the concept and report some preliminary characteristics of this novel analysis.

## 1. Introduction

The *Fermi* Large Area Telescope (*Fermi* LAT) is an instrument on the *Fermi*  $\gamma$ -ray telescope operating from 20 MeV to over 300 GeV. The instrument is a  $4 \times 4$  array of identical towers, each one consisting of a tracker-converter (TKR), based on Silicon detector layers interleaved with Tungsten foils, where the photons have a high probability of converting to pairs, which are tracked to allow reconstruction of the  $\gamma$ -ray direction and a segmented calorimeter (CAL), made of CsI crystal bars, where the electromagnetic shower is partially absorbed to measure the  $\gamma$ -ray energy. The tracker is covered with an anti-coincidence detector (ACD) to reject the charged-particle background. Further details on the LAT, its performance, and calibration are given by [1] and [2].

Most of the science done with *Fermi* LAT spans photons with energies from 50 MeV to about 10 GeV, where the sensitivity of the instrument is good and the available number of detected photons high. However, there are many sources which emit  $\gamma$ -rays above a few tens of GeV. These energies that are almost accessible by the current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs). Even though the detection area of LAT is small (in comparison to that of IACTs), *Fermi* LAT provides all-sky coverage and a very high duty cycle, which are crucial characteristics for producing  $\gamma$ -ray source catalogs and study source variability in an unbiased way. A prime example is the first *Fermi* LAT catalog of  $>10$  GeV sources (1FHL) [3], which contains 514 sources, out of which  $\sim 100$  sources have already been detected at very high energies ( $>100$  GeV, or VHE), and  $\sim 200$  additional sources have been identified as good candidates to be VHE emitters and be detected with IACTs.

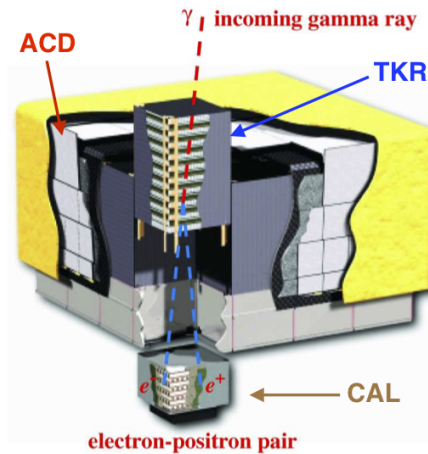


Figure 1: Schematic diagram of the Large Area Telescope. The telescopes dimensions are  $1.8\text{m} \times 1.8\text{m} \times 0.72\text{m}$ . [1]

The performance of *Fermi* LAT above 10 GeV is excellent. The angular resolution and signal/background separation is best at the highest photon energies, where one only suffers from a slight deterioration of the energy resolution due to the fact that the showers are no longer contained in the calorimeter. However, the steep falling photon flux with energy of most  $\gamma$ -ray sources, together with the relatively small effective area of LAT ( $\sim 1\text{m}^2$ ), results in a substantial limitation due to the very low number of detected photons (e.g., in the 1FHL, many sources were characterized with only 4–5 photon events over a background signal of 0–1 event). The low statistics from  $\gamma$ -ray sources is going to be an even larger problem for the second *Fermi* high-energy LAT catalog (2FHL,

in preparation), which is expected to consist on  $\gamma$ -ray sources detected above 50 GeV (instead of 10 GeV).

In these proceedings we report an analysis which can help increase the photon statistics at few tens of GeV, hence improving the ability to perform science at the highest LAT energies, where the IACTs start operating. The methodology is still being developed. Here we only present the concept and report some preliminary characteristics.

## 2. The Calorimeter-only (CalOnly) Fermi-LAT analysis

The regular *Fermi* LAT event classes require usable information from the TKR. This is a sensible approach, given that the TKR information is crucial to determine accurately the incoming direction of the  $\gamma$ -ray event. The LAT TKR comprises only  $\sim 1.5$  radiation lengths (on axis), which means that a large fraction of  $\gamma$ -rays from the astrophysical sources are discarded at the very beginning of the analysis because they do not convert in the TKR, or they convert in the bottom layers and the TKR information is not sufficient for a proper determination of the incoming direction of the  $\gamma$ -ray event. This situation is depicted in Figure 2.

In the standard LAT analysis, the CAL is essentially used for signal/background separation (together with the TKR and ACD) and to determine the energy of the  $\gamma$ -rays and electrons. The LAT has a hodoscopic calorimeter, consisting of 16 towers with 8 layers of 12 crystals each because of three driving reasons. First, shower profiling improves energy reconstruction. Next, shower topology contains valuable information for signal/background separation. Last, it realizes independent event acceptance and reconstruction.

To create a usable event class without using TKR information, one must determine the incoming direction of the  $\gamma$ -rays with sufficient resolution (a few degrees) while keeping a reasonable background rejection ( $\sim 0.999$ ). This would increase the number of available high-energy events for performing  $\gamma$ -ray astronomy. The above mentioned (non-standard) LAT analysis, dubbed Calorimeter-only (CalOnly) analysis, is currently being developed by the *Fermi* LAT collaboration, and is aimed to deliver yet another class of events, the CalOnly event class, which may be added to the other photon event classes coming from the regular LAT analysis. For the CalOnly analysis, it fully reconstructs the electromagnetic showers and determine its main axis, which points to the direction of the incoming  $\gamma$ -ray event.

Since the main event trigger for LAT is based on the TKR, those events with no usable TKR information have a low chance of being recorded and trans-

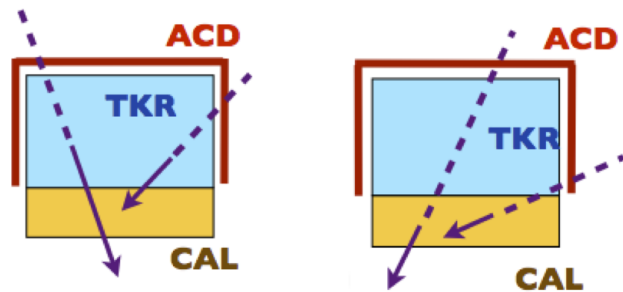


Figure 2: The left panel depicts two events that convert to electron pairs in the TKR (from the broken lines to the solid lines in these figures). These events would be used in the regular *Fermi* LAT analysis. The right panel shows two events without usable TKR information. One is a side-entering event that goes through a small fraction of the TKR. The other one crosses the entire TKR, but converts to an electron pair in the CAL. These two events would be rejected and not be used for regular LAT analysis. These are the type of events which could be recovered with a dedicated analysis that does not require TKR information, the so-called CalOnly events.

ferred to the ground. However, large energy depositions in CAL generate a trigger that is fully independent of TKR, and on-board event selection records events that deposit energy larger than 20 GeV in CAL. Consequently, the CalOnly event class will only be effective above a few tens of GeV.

### 2.1. Pass 8

The development of the CalOnly analysis is done in the context of Pass 8, which is the new iteration of the LAT event-level analysis package. Pass 8 was originally designed to address the effect of coincidences with cosmic rays ('ghost' events), but quickly evolved in a comprehensive revision of the instrument simulation, the event reconstruction, and the background rejection, with the goal of improving all the aspects of the LAT performance: larger acceptance, better angular and energy resolution, and extension of the energy reach below 100 MeV and in the TeV range.

The details on the Pass 8 analysis chain can be found in [4]. The CAL reconstruction begins with a clustering stage that tries to isolate the genuine  $\gamma$ -ray shower from smaller energy deposition due to ghost events. At this point we can exploit the segmentation of the CAL to identify the energy deposition centroid and the shower axis (via a moment analysis) that, for CalOnly, corresponds to the photon incoming direction. This direction is propagated to the ACD (in addition to the tracks from the tracker) in order to associate energy deposition in the tiles and discriminate charged particle without the TKR direction. This is one of the main improvements introduced with Pass 8 and proved to be very useful even if its separation

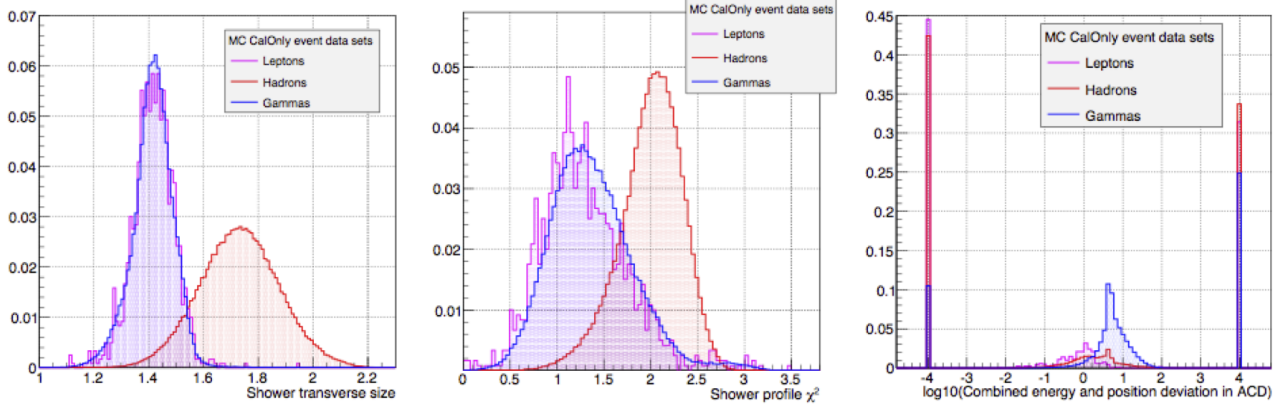


Figure 3: The left, middle and right panels show the logarithm of the CAL first cluster transverse profile RMS, the logarithm of  $\chi^2$  of the profile fit computed over a 100mm radius cylinder around the trajectory, and the logarithm of combined energy and position deviation in ACD respectively. The last one needs some more description. It is the number of sigmas less than an expected MIP signal, combined with the number of sigmas the track propagation is away from tile or ribbon most likely to veto the first CAL cluster and the number of sigmas the energy deposited in the ACDs is away from the expected amount. If the value of this combined quantity is zero, then the  $\log_{10}$  of this quantity is set to -4. This is more likely to happen to MIPs than for  $\gamma$ -rays. If there are no tracks associated to ACD signals, this quantity is set to +4. Charge particles are likely to have smaller values than the  $\gamma$ -rays.

capability is limited by the angular resolution of the CAL, that is obviously worse than that of the TKR..

Another important improvement in the CAL reconstruction is the energy measurement that, for CalOnly, is based on a full three-dimensional fit of the shower energy deposition. This method needs a precise modeling of the longitudinal and lateral development of showers inside the CAL and a reference axis. The latter, usually taken from the tracker, can be obtained from the aforementioned moment analysis with a small change in performance.

The last step of the Pass 8 development is the high-level analysis that links together all the outputs of the reconstruction and classify events as good  $\gamma$  rays or not. This is the core of the CalOnly development and is described in next section.

## 2.2. Signal / Background separation

The *Fermi* LAT needs to reject a cosmic-ray background that outnumbers the signal ( $\gamma$  rays) by many orders of magnitude, and hence an efficient signal/background separation (rejecting  $10^{3-4}$  of the background events) is required to be able to perform  $\gamma$ -ray astronomy. The LAT background consists mostly on protons and electrons, but also on alpha particles and heavy nuclei. As the  $\gamma$ -ray energy increases, we have a natural improvement in the signal/background ratio due to the fact that most  $\gamma$ -ray sources have spectra that can be parameterized with power-law indices harder than 2.5 (often even harder than 2.0), while the spectra of the proton background follows a power-law index of  $\sim 2.7$  and that of the electrons a power-law index of  $\sim 3.1$ .

The rejection of the background cosmic-ray events in the CalOnly analysis is based on the different topology of electromagnetic and hadronic showers, and the ACD signals produced by the charged particles. It is worth noting that, while protons and heavy nuclei can be effectively distinguished from  $\gamma$  rays using only information from the CAL, the electrons/positrons produce electromagnetic showers that are essentially identical to those of the  $\gamma$  rays, and hence the information from the ACD is crucial to be able to reject electrons. The left and middle panels in Figures 3 show the normalized MC distributions of two CAL-related parameters that can effectively distinguish between electromagnetic (*gammas* and leptons) and hadronic showers. In order to be able to reject the leptons, one needs the help of ACD-related parameters, as depicted in the right panel in Figure 3.

In order to maximize the separation of signal and background, instead of making simple cuts in the distributions of CAL and ACD parameters as the ones shown above, we perform the analysis through a multivariate analysis (MVA) that uses a large number of CAL and ACD parameters. For the most effective background rejection, we applied the Boosted Decision Tree (BDT), one of the methods of multi-variate analysis. In this method, we train many classification trees with Monte Carlo (MC) data, for which can identify unambiguously what is signal and what is background. We are using the ROOT-based TMVA package to train the classification tree analysis [5]. We build the trees and then evaluate the gamma-likeness of each event. Next we can cut on the gamma-likeness and get the events classified as signal or background. By selecting events with a very high gamma-likeness,

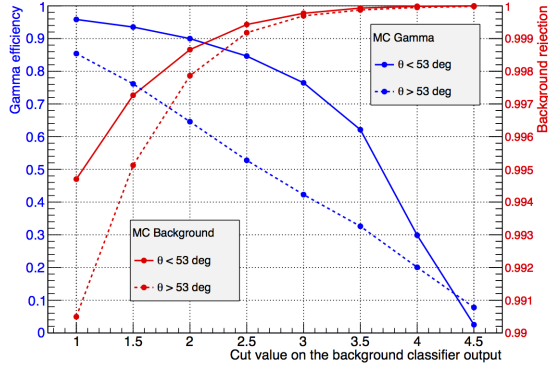


Figure 4: Efficiency of MC  $\gamma$  events (blue) and rejection of MC background events (red) vs. cut value of a classifier output.

one can increase the purity of the selected data set, but at the expense of reducing the number of  $\gamma$ -ray candidates. This is represented in Figure 4. The optimal value to increase the signal/background is typically obtained for a cut value between 2 and 3 (dependent on the energy range and incidence angle of the  $\gamma$ -ray considered).

At the present time we are optimizing the classification tree by modifying the input CAL and ACD parameters (including creating new composite variables), as well as by building the classification trees in different modes. Consequently, the results presented in this proceedings should be considered as preliminary, and likely reporting a lower limit of the actual performance of the CalOnly analysis.

### 2.3. Quality of the reconstructed events

In this section we address the quality of the reconstructed CalOnly events (after signal/background separation) using dedicated MC simulations of  $\gamma$ -ray events.

Two basic quantities are being evaluated: the angular and the energy resolution. Given that the thickness of the calorimeter increases rapidly with the incidence angle, one expects a different performance for low and high incidence angle  $\gamma$  rays. In this section we define low (high) incidence angle as smaller (larger) than 53 degrees ( $\cos(53^\circ) \sim 0.6$ ) and evaluate the performance for these two cases. And naturally, as it occurs in the regular *Fermi* LAT analysis, the performance can also vary with the energy of the incoming  $\gamma$  ray. Here we define low (high) energy as being in the range  $\sim 30$ -100 GeV ( $\sim 100$ -300 GeV), and evaluate the performance for these two energy bands.

Figure 5 shows the normalized distributions in the error of the reconstructed directions for low/high energy bands and incidence angles. The angular resolution can be defined as the 68% containment in those

distributions (PSF68), which would result in  $\sim 2$  degrees for high inclination  $\gamma$  rays, and  $\sim 3$ -4 degrees for low inclination  $\gamma$  rays (with a relatively small dependence on the energy). The PSF68 for regular LAT photons (i.e. with usable TKR information) at these energies is  $\sim 0.1$ -0.2 degrees, which is more than one order of magnitude better than for CalOnly photons.

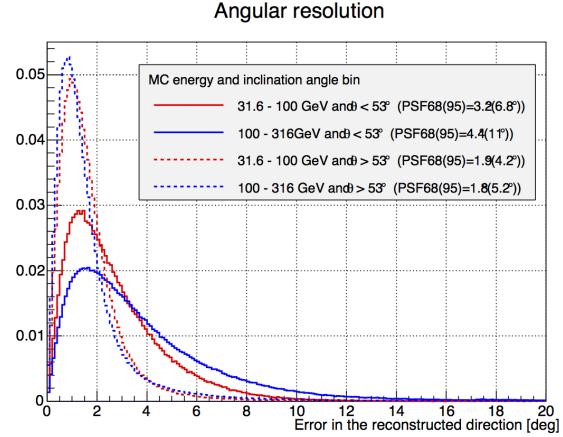


Figure 5: Normalized histograms of the angular distances between reconstructed and MC direction of CalOnly events in 2 inclination angle  $\times$  2 energy bins.

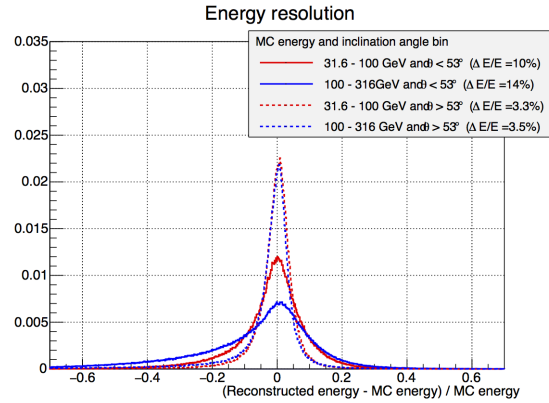


Figure 6: Normalized histograms of the dispersions in the reconstructed energy of MC CalOnly events in 2 inclination angles  $\times$  2 energy bins.

Figure 6 shows the normalized distributions in the error of the reconstructed energies for low/high energy bands and incidence angles. The energy resolution can also be defined as the 68% containment on these distributions, and using the largest distance from the peak position to the edge of the 68% containment. The energy resolution is  $\sim 3$  - 4% for high inclination and  $\sim 10$  - 15% for low inclination  $\gamma$ -rays, with little dependence on the energy of the event. This performance is very close to that of regular LAT photons. The quality of the energy reconstruction is mainly connected to the path length of shower axis (related

to the shower containment) and the accuracy of the shower direction reconstruction. While the latter is worse for CalOnly events, this class can benefit from a larger field of view and therefore longer trajectories. It must be noted that both direction and energy resolution can be improved with a dedicated selection of good quality events, at the price of a lower effective area. The best trade off between these conflicting requirements is still to be evaluated.

### 3. Conclusions

Pass 8 provides an unprecedented framework to develop an analysis that uses events without usable TKR information.

The CalOnly event class, currently under development within the Fermi-LAT collaboration, could be used to increase the acceptance of *Fermi* LAT above few tens of GeV (where the performance is photon statistics limited), by recovering for astronomical studies  $\gamma$ -ray events without usable TKR information. This implies that CalOnly events will have a worse signal/background separation and angular resolution, when compared to the regular LAT events. However, they can have a better energy resolution, if considering the high incidence angle events.

The CalOnly event class may be particularly relevant in the following two scientific topics:

- Search for line-signals potentially coming from Dark Matter annihilation (because of the larger number of events and the excellent energy resolution for the large-incident angle events)
- Study of transient events like GRBs and AGN flares (because of the larger number of events and the valuable increase in the temporal coverage of the source)

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